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Abstract

Beyond energy efficiency, China also actively pursues non-fossil energy development to curb energy demand and carbon emissions, targeting a 15% non-fossil share of total energy consumption in 2020 with targeted programs encouraging the growth of renewable and nuclear energy. While these policies help address technological and institutional barriers to China's alternative energy development, the life-cycle resource and energy inputs to alternative energy technologies (AET) are rarely evaluated and thus difficult to address in target-setting and policy formulation.

This paper presents a new cradle-to-grave evaluation of China's alternative energy development by integrating bottom-up modeling of two scenarios of different paces of AET capacity expansion from 2010 to 2030 with simplified lifecycle analyses of water and energy inputs to each type of AET. The results show that China's projected renewable development will require 30 to 50 Mt of water annually, mostly from wind power development but also from growing solar concentrated solar power. Besides the sheer magnitude of water needed for capacity expansion on the scale needed to achieve China's planned renewable energy development are various other water-related problems, the detrimental effects of rare earth metal mining on water and air quality are gaining visibility, challenging the image of wind and solar power as clean energy sources. These problems illustrate that future renewable energy development will be closely linked to if and how water concerns and related social and environmental problems are addressed, and suggest that renewables should be integrated with other efforts such as energy efficiency to shape China's energy future.

Introduction

As the world's leading electricity consumer and annual CO₂ emitter, China has increasingly looked to renewable energy for meeting its rapidly growing electricity demand. Over the last three decades, China's electricity consumption has grown at an astounding average annual rate of over 9.5% and more recently at over 13% per year in the last decade due to economic growth, urbanization and industrialization (National Bureau of Statistics, 2010). The unprecedented growth in electricity demand has worsened power shortages to an all time high of 30 GW predicted for the summer of 2011 (Xinhua, 2011). At the same time, China has pledged to meet a 40% to 45% reduction in CO₂ emissions per unit GDP from 2005 levels by 2020 as well as 16% and 17% reduction in energy and CO₂ emissions per unit GDP, respectively, during the 12th Five Year Plan Period.

To curb growth in energy demand while simultaneously reducing CO₂ emissions, China has actively pursued renewable energy development in recent years and is striving to meet 11.4% of its total energy consumption from renewable sources by 2015 and 15% by 2020. China is now the world leader in overall renewable energy finance and investment as well as wind turbine and solar PV module production (Pew Charitable Trusts, 2011). But as China's renewable sector continues to grow, an important constraint will be the water resources needed to build and to operate and maintain the new solar, wind and large hydro power plants. A closer look at the cradle-to-grave lifecycle of planned solar photovoltaic (PV) and concentrated thermal, wind and large hydro reservoir power generation technologies reveal that China's thirst for clean energy will lead to demand for more water.

Evolution of China's Renewable Sector

Renewable and alternative energy development has received regulatory and financial support under a flurry of laws and regulations in China over the last decade. The 2005 Renewable Energy Law and its 2009 amendments mandated market shares and purchase of renewable power generation and launched feed-in tariffs for biomass and wind power. The 2007 Medium and Long-term Development Plan for Renewable Energy set official capacity targets for the first time, which have since been revised upward in the 2010 Draft Development Plan for Emerging Energy Technologies (see Table 1).

Table 1: Renewable Development Milestones

	2010 Target	2010 Actual	2020 Target	Revised 2020 Targets (as of 2011)
Total Renewable Power	195	259	332	470
Hydropower	190	213	300	300
Wind	5	45	30	150
<i>Off-shore</i>	0.2		1	
<i>On-shore</i>	4.8		29	
Solar Power	0.3	0.9	1.8	20
PV Total	0.3		1.6	
Solar Thermal	0.1		0.2	

Sources: 2010 and 2020 targets from 2007 Medium and Long-term Development Plan for Renewable Energy in China; 2010 actual from National Energy Administration, 2011; Revised 2020 targets from 2011 Draft Plan for National Economic and Social Development (National Development and Reform Commission, 2011).

As a result of these strong policy drivers, China met all of its 2010 renewable targets and also became the world leader in total installed clean energy capacity with unprecedented investment in grid construction and expansion. The most recent accomplishments of China's renewable sector include:

- *Wind*: onshore wind power capacity doubled every year since 2005 with 18.9 GW added in 2010 alone, and first commercial offshore wind farm (102 MW) in operation
- *Solar PV*: installed capacity more than tripled from 45 MW in 2008 to 160 MW in 2009
- *Concentrated Solar Thermal*: 1.5 MW pilot concentrated solar power (CSP) tower plant under development in Beijing
- *Large Hydro*: annual growth rates of 10% since 2000 with doubling of installed capacity from 2005 to 2010

While certainly impressive, the growth in China's renewable sector has also masked crucial barriers and resource constraints facing the massive deployment of renewable technologies on a scale needed to sustain planned economic growth of over 7% per year through 2015 and the subsequent energy demand. For relatively new technologies that have not achieved commercialization such as concentrated solar towers, China faces many technical limitations in expanding the scale of installed capacity. Others such as hydropower have been slowed by uneven and often changing market and policy support. The renewable leaders of wind and solar PV have also encountered physical and institutional barriers to grid integration.

Policies, market reform and investment can help overcome these technological and institutional barriers, but the hidden material and particularly water resource constraints to renewables are more difficult to address. Continuing the growth of installed wind capacity requires manufacturers to churn out more wind turbines, but there is increasingly limited supply of neodymium for wind turbines' high strength magnets. Besides competing demand for neodymium from motors, sound equipment and even Priuses, severe air and water pollution problems with its mining and processing have emerged (see Box 1).

Likewise, advanced thin-film solar PV cells require rare earth metals such as indium, gallium, selenium and cadmium telluride but also face limited virgin resources and rising demand from flat panel displays, electronic and wireless applications. While China has already grasped the threat of rare earth metal shortage by establishing a tightly controlled export quota system and imposing taxes on mining, the looming shortage of water resources for renewable development has gone largely unnoticed.

Box 1: Water Contamination from Rare Earths Mining

Neodymium is one of seventeen rare earth elements and forms the basis of the chemical compound $\text{Nd}_2\text{Fe}_{14}\text{B}$ used in high-strength permanent magnets driving motors and generators, with nearly a ton of magnet needed per MW of wind capacity (Lifton, 2010). Rare earth elements are typically dispersed in

Earth's crust and are often produced as by-products of other metals or through reprocessing. In the case of neodymium, China accounts for over 80% of global supply and its 2007 annual production of 50,000 tons of Nd₂Fe₁₄B magnets is expected to double within the next five years (Shenzhen Juke Co., 2008). In 2010, the estimated global annual production of neodymium was 21,307 tons, of which 90% of extraction and processing is in China, which is also home to 93% of the world's rare earth minerals (US Department of Energy, 2010 and Bradsher, 2010). Neodymium extraction and processing – along with the mining and processing of other rare earth metals – have severe environmental consequences in toxic air and water pollution that are already being felt in villages throughout China. Near the city of Baotou in Inner Mongolia, seven million tons of waste including radioactive tailings from neodymium processing is discharged annually into a local lake along with toxic dust and airborne radiation (Parry, 2011). Over two hundred illegal make-shift rare earth mines in the villages of Guangdong province were also closed down, where waste runoff to the local river were reported to have contaminated local reservoirs and destroyed fish-farm stock and rice crops (Lee, 2008).

Water for Renewable Development

Life-cycle analyses of renewable energy technologies in China and abroad highlight the high water input requirements needed to sustain renewable development¹ (see Table 2). Of all the renewable energy technologies, concentrated solar tower requires by far the most water with a lifetime average of 48,000 tons of water per MW of installed capacity (a large coal-fired or nuclear power plant typically have installed capacity of 1000MW). Huge amounts of water are required on a daily basis for different processes of operating and maintaining concentrated solar towers, even though the pilot solar tower in China has very small installed capacity (see Figure 1). The daily 200 tons of water consumption is equal to the *annual* tap water consumption for three Chinese residents². Over its twenty year lifetime, China's pilot solar tower would consume 73,000 tons of water. Although the technology is too nascent for water to be a constraining factor now, the development of large-scale, water-intensive solar CSP tower in the western solar-rich regions of China will intensify the demand for water in an already water-scarce region.

¹ Geothermal power generation is not discussed due to its limited scale and applications. Nuclear power is also excluded due to complex water boundary issues regarding the use of recirculating and cooling water and seawater.

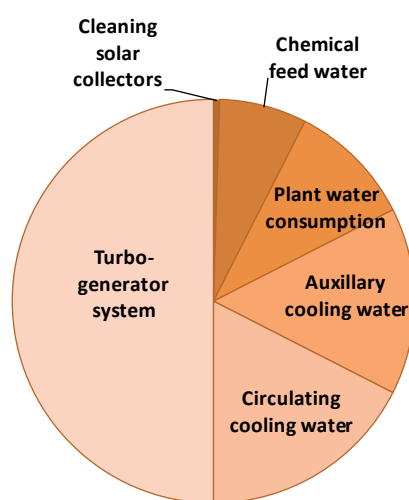
² According to NBS, the 2009 reported daily per capita tap water consumption for residential use was 176 liters, or 0.176 metric tons per person (NBS, 2010).

Table 2: Lifetime Water Requirement for Renewables and Potential Growth in China

	Renewable Energy Technology	Lifetime Water Requirement (tons/MW)	2010 Share of Installed Capacity	Possible 2030 Share of Installed Capacity*
Hydro	Large Hydro Reservoir	154	22%	16%
Solar PV	Cadmium indium gallium selenide (CIGS)	25	All PV: 0.1%	0.2%
	Mono Silicon Crystalline	494		-
	Poly Silicon Crystalline	494		1.6%
	Amorphous Silicon Crystalline	615		0.2%
Wind	On-Shore	1,767	3%	14%
Concentrated Solar	Concentrated Solar Tower	48,667	-	0.2%

Sources: hydro water intensity based on study of Brazil's Itaipu Dam (Ribeiro & da Silva, 2010); solar PV data from European PV studies in Jungbluth, Stucki & Frischknecht, 2009; wind from Chinese study of 30 MW on-shore wind farm in Guangxi (Chen, Yang & Zhao, 2011); solar tower data from Chinese pilot plant under development in Beijing (Chen, Yang, Zhao & Wang, 2011). 2010 installed capacity shares calculated from data given in National Energy Administration, 2011.

**Note: Possible 2030 share of installed capacity based on LBNL China Energy End-Use Model power sector module, with the underlying assumption that China meets all of its 2020 capacity targets and that installed capacity continues to grow at similar paces through 2030. More details given in Zheng and Fridley, 2011.*



Breakdown of Solar Tower's Daily Water Consumption of 200 tons

Figure 1: Chinese Solar Tower Daily Water Use

Source: Chen, Yang, Zhao, & Wang, 2011.

Water is also needed to construct and maintain China's growing fleet of wind turbines, with the second highest water input requirement per MW of capacity. Although the 1767 tons of water needed per MW of wind development is lower than coal-fired power plants, the rapid scale of planned deployment with capacity target of 150 GW by 2020 translates into growing shares of total water consumption.

Solar PV is interesting in that the lifecycle water intensities for different types of solar cells range from a very low 25 tons/MW for advanced thin-film CIGS solar to a high of 615 tons/MW for amorphous silicon crystalline cells. Most of the water for solar PV development is used in power plant operations and related infrastructure. Poly-silicon crystalline PV, which is expected to dominate the solar PV market in coming years, needs nearly 500 tons/MW with 14 GW total possible by 2020 to meet the total solar PV target of 20 GW.

Hydropower, China's largest source of renewable power, has relatively low lifetime water requirements for reservoir dam construction and operation due to its very long lifetime of 100 years. However, the future development of hydroelectric dam projects will depend largely on water availability of China's rivers, as even the Three Gorges Dam was recently ordered to release stored water for irrigation and drinking water during one of the worst droughts for the Yangtze River delta. The severe droughts in Central and South China this year has already led to extremely low water levels in reservoirs and lakes and threatens to reduce or stop hydropower generation, exacerbating electricity shortages.

Long-term Water Implications for Renewables

Over the next twenty years, if China is to meet its renewable targets and continue to undertake energy efficiency improvements to slow growth of electricity demand, its renewable development would still require between 30 and 50 million tons of water annually³. Most of this water requirement is from the expansion of wind power and the slower but growing development of solar CSP (see Figure 2). The cumulative water demand from 2010 to 2030 for renewable development of 813 million tons equals nearly a year's worth of total water supply for all Beijing residents or for the entire state of Maine (NBS 2010, USGS 2009).

³ This is derived from a "Continued Improvement" scenario of continual energy efficiency improvements and renewable capacity expansion at pace that allows China to meet all of its 2020 targets and continue growing thereafter. More details on the scenario and assumptions are given in Zheng & Fridley, 2011.

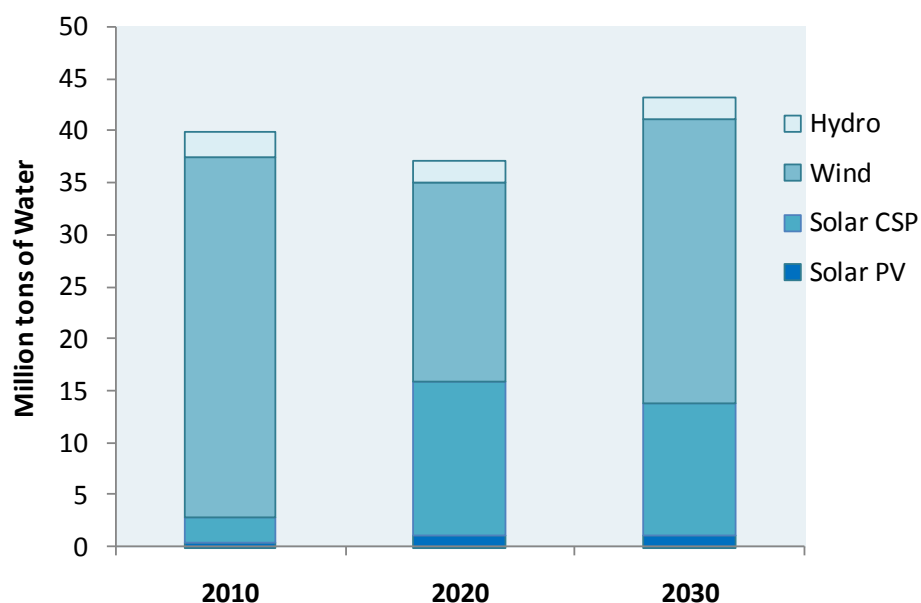


Figure 2: Annual Water Use for China's Renewables

Source: Zheng & Fridley, 2011.

More problematic than the total water demand for renewable development is the geographical disparity in resource availability between water and renewable energy. Both wind and solar resources are abundant and heavily concentrated in the remote regions of Northwestern China, where water resources are scarce. This is especially true in the case of wind development, where majority of the unprecedented growth has taken place in some of the most water-constrained provinces of China. Inner Mongolia, the leading province for wind development with one-third of the total installed wind capacity in 2009, is ranked 20 out of 31 in terms of water resources. Likewise, the other three of the top four provinces in terms of installed wind capacity are all in the bottom 10 provinces in terms of water resource availability (see Table 3). Regional water availability will become an increasingly important constraint in China as it advances its renewable development.

Table 3: Wind Development and Water Resource Availability

	2009 Installed Wind Capacity (MW)	Total Available Water Resources (billion tons)	2009 Wind Capacity Rank	Water Resources Availability Rank
Inner Mongolia	9196	37.8	1	20
Hebei	2788	14.1	2	26
Liaoning	2425	17.1	3	25
Jilin	2064	29.8	4	22
Heilongjiang	1709	98.9	5	8
Shandong	1229	28.5	6	23
Gansu	1188	20.9	7	24
Jiangsu	1097	40	8	19
Xinjiang	1003	75.4	9	14

Sources: Data from Cheung, 2011 and NBS, 2010. Ranking done by author based on data.

Conclusions

In spite of a global economic downturn, China's renewable energy development has been plowing full steam ahead in the last few years. The extraordinary doubling of installed capacity for wind on an annual basis and the tripling of solar PV installed capacity from 2008 to 2009 have been met with optimism from policymakers with future targets continually revised upwards. Against China's promising future of renewables is a palpable disconnect in recognizing the water-energy nexus, or in this case, the energy requirements for renewable energy development. Besides the sheer magnitude of water needed for capacity expansion on the scale needed to achieve China's planned renewable energy development are various other water-related problems, the detrimental effects of rare earth metal mining on water and air quality are gaining visibility, challenging the image of wind and solar power as clean energy sources. Large hydro dams have very low lifetime water input requirement but faces barriers in the form of water shortage due to droughts and water rights management. Regional variations in water resource availability will also determine the extent to which water will be a limiting factor for solar and wind development. These problems illustrate that future renewable energy development will be closely linked to if and how water concerns and related social and environmental problems are addressed, and suggest that renewables should be integrated with other efforts such as energy efficiency to shape China's energy future.

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